# POLYMER BASED MULTIMODE INTERFERENCE OPTICAL DEVICES

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# DEDICATION

**Specially dedicated to my beloved parents, Ibrahim and Jamaliah;
my wife, Fauziah and my lovely daughter, Nur Izzatul Afiqah for their
continuous support, prayers and understanding.**

**~ With Love and Respect ~**

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# ABSTRACT

A research on polymer based optical waveguides and devices have been a topic of great interest in optical communications due to its pertinent advantages which include versatility and reduction in fabrication cost. This thesis is significantly devoted towards the first ever development of single mode optical waveguides and multimode interference (MMI) interconnecting devices based on photosensitive BenzoCyclobutene (BCB 4024-40) polymer. The developed MMI optical devices are splitters, splitter-combiner, cross couplers and Wavelength Division Multiplexing (WDM) coupler. These development process can be divided into four essential stages; material characterization, design and modelling, fabrication and device characterization. In each stage, several important techniques and equipments have been employed. The devices are fabricated on BK7 glass substrate and thin film of silica as a clad using soda lime glass mask of ±0.2 μm resolution. A relatively high propagation loss of 3.55 dB/cm has been observed for single mode waveguide structure, which is due to the resulting sidewall roughness. The splitting uniformity of symmetric MMI splitters were found to be better than 0.6 dB and the insertion loss for all splitter structures were measured to be less than 1.5 dB at 1550 nm wavelength. The 1×2 splitters were interconnected to function as a splitter-combiner which is ideally used as a basic building block for Mach-Zehnder Interferometer. The measured structure yielded an insertion loss of 1.85 dB for device size of 4.2 mm. The insertion loss of the 2×2 and 3×3 cross couplers based on general and paired interference were measured and found to be between 2.5 to 3.5 dB for 6 mm to 10 mm of cavity size. A 1310 nm and 1550 nm WDM coupler is demonstrated in which the device is designed based on a combination of general interference and paired interference mechanisms. The measured crosstalk at 1310 nm is -14.42 dB and at 1550 nm is -20.61 dB. The measured insertion losses were in the range of 3.2 to 3.5 dB for MMI cavity size of 7 mm. A novel 1×2 MMI thermal photonics switch is proposed. The switch uses a ridge waveguide of BCB 4024-40 polymer on silica clad. The proposed structure works well with crosstalk level of -28 dB and low switching power. Significantly, this research has successfully demonstrated the possibility of applying a photosensitive BCB 4024-40 polymer in the low cost development of integrated optics components.

# ABSTRAK

Penyelidikan bagi pandu gelombang dan peranti optik berasaskan bahan polimer telah menjadi topik yang diminati di dalam perhubungan optik disebabkan oleh beberapa kelebihan termasuk kebolehubahan dan pengurangan kos. Tesis ini adalah berkaitan dengan pembangunan pandu gelombang mod tunggal dan peranti penghubung saling ganggu pelbagai mod (MMI) yang berasaskan kepada bahan polimer peka cahaya, BenzoCyclobutene (BCB 4024-40). Peranti yang dibangunkan adalah pemisah, gabungan pemisah-pencantum, pengganding dan pengganding WDM. Proses pembangunan ini boleh dibahagikan kepada empat turutan penting iaitu pencirian bahan, rekabentuk dan pemodelan, fabrikasi dan pencirian peranti. Pada setiap turutan, pelbagai teknik penting dan peralatan telah digunapakai. Fabrikasi peranti dilakukan di atas substrat kaca BK7 dan filem nipis $SiO_2$ sebagai penutup menggunakan topeng kaca soda dengan resolusi ±0.2 µm. Kekasaran pada dinding pandu gelombang telah mengakibatkan nilai kehilangan perambatan yang tinggi iaitu 3.55 dB/cm bagi pandu gelombang mod tunggal. Keseragaman pemisahan bagi pemisah MMI simetri menunjukkan nilai yang kurang dari 0.6 dB bagi semua struktur pemisah. Kehilangan masukan telah diukur sebagai kurang dari 1.5 dB bagi semua struktur pemisah pada panjang gelombang 1550 nm. Gabungan pemisah dan pencantum menghasilkan kehilangan masukan sebanyak 1.85 dB bagi panjang kaviti sebanyak 4.2 mm. Pengganding MMI 2×2 dan 3×3 yang berasaskan saling ganggu am dan saling ganggu pasangan telah dihasilkan dan kehilangan masukan 2.5 hingga 3.5 dB telah direkodkan bagi panjang kaviti di antara 6 mm hingga 10 mm. Pengganding WDM bagi panjang gelombang 1310 nm dan 1550 nm telah dihasilkan berdasarkan kepada gabungan saling ganggu am dan saling ganggu pasangan. Cakap silang yang telah diukur adalah -14.42 dB bagi 1310 nm dan -20.61 dB bagi 1550 nm. Manakala kehilangan masukan adalah 3.2 hingga 3.5 dB bagi panjang kaviti sebanyak 7 mm. Struktur suis optik MMI 1×2 berasaskan kesan kawalan haba telah dicadangkan buat pertama kali. Pandu gelombang polimer BCB 4024-40 berstruktur *ridge* di atas bahan silika digunakan sebagai struktur rekabentuk. Struktur ini menghasilkan cakap silang serendah -28 dB dan kuasa pensuis yang rendah. Kajian ini telah berjaya menunjukkan kebolehan polimer sensitif cahaya, BCB 4024-40, di dalam pembangunan kos rendah komponen optik bersepadu.

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# LIST OF SYMBOLS

| SYMBOLS | | DESCRIPTION |
|---|---|---|
| $n$ | - | Refractive index |
| $E$ | - | Electric field |
| $H$ | - | Magnetic field |
| $D$ | - | Electric field density |
| $B$ | - | Magnetic field density |
| $\rho_v$ | - | Electric charge density |
| $J$ | - | Current density |
| $\mu$ | - | permeability |
| $\varepsilon$ | - | permittivity |
| $k$ | - | Wave vector |
| $\beta$ | - | Propagation constant |
| $\lambda$ | - | Operating wavelength |
| $\phi$ | - | Phase shift |
| $\gamma$ | - | Transverse propagation constant |
| $n_{eff}$ | - | Effective index |
| C | - | Successive over Relaxation (SOR) parameter |
| $\alpha$ | - | Degree of implicitness |
| $b$ | - | Normalized propagation constant |
| $w$ | - | Staircase structure width |
| $\Delta s$ | - | Slope side wall distance |
| $\theta$ | - | Slope angle |

| | | |
|---|---|---|
| $W_M$ | - | Multimode waveguide width |
| $L_M$ | - | Multimode waveguide length |
| $L_\pi$ | - | Beat length |
| $c_\upsilon$ | - | Modes coefficient |
| $\upsilon$ | - | Modes number |
| $p$ | - | Periodic nature of imaging along multimode waveguide |
| $\xi$ | - | Propagation loss |
| $C_C$ | - | Coupling coefficient |
| $R$ | - | Reflection coefficient |
| $P$ | - | Optical power |
| $\dot{Q}$ | - | Distributed thermal source perunit volume |
| $p_m$ | - | Density of material |
| $C_H$ | - | Specific heat |
| $T$ | - | Temperature |
| $h$ | - | Heat transfer coefficient |
| $q$ | - | Convective heat flux |

# LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| AFM | - | Atomic Force Microscope |
| AO | - | Acousto-Optic |
| BCB | - | BenzoCyclobutene |
| BPM | - | Beam Propagation Method |
| CVD | - | Chemical Vapor Deposition |
| CWDM | - | Coarse Wavelength Division Multiplexing |
| DFB | - | Distributed Feedback |
| EIM | - | Effective Index Method |
| EO | - | Electro-Optic |
| FDM | - | Finite Difference Method |
| FFT-BPM | - | Fast Fourier Transform Beam Propagation Method |
| HPM | - | High Power Microscope |
| IPA | - | Iso-Propyl Alcohol |
| MMI | - | Multimode Interference |
| MO | - | Magneto-Optic |
| MZI | - | Mach-Zehnder Interferometer |
| NO | - | Nonlinear-Optic |
| OEIC | - | Optoelectronic Integrated Circuit |
| PCM | - | Prism Coupling Method |
| PECVD | - | Plasma Enhanced Chemical Vapour Deposition |
| PMF | - | Polarization Maintenance Fiber |
| PMMA | - | Polymethyl Methacrylate |
| RIE | - | Reactive Ion Etching |

| | | |
|---|---|---|
| SEM | - | Scanning Electron Microscope |
| SOR | - | Successive Over Relaxation |
| TBC | - | Transparent Boundary Condition |
| TE | - | Transverse electric |
| TM | - | Transverse magnetic |
| TO | - | Thermo-Optic |
| WDM | - | Wavelength Division Multiplexing |
| 2D-FDBPM | - | Two Dimensional Finite Difference Beam Propagation Method |
| 2D-FDTM | - | Two Dimensional Finite Difference Thermal Modelling |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of Research

The transmission and processing of signals carried by optical beams has been a topic of great interest since the early 1960s. It is time when the development of the first laser provided a stable source of coherent light for such application. Thus, the concept of optoelectronic integrated circuits (OEICs) emerged which have two distinct goals (Tien, 1977): one is to apply thin-film technology to the formation of optical devices and circuits; the other is to integrate a large number of optical components on a single substrate. In essence, it is to utilize thin-film based monolithic optical circuits to generate, guide, modulate, split/combine, route and detect light, reminiscent of the integrated circuits in microelectronics. This concept was first proposed by Stuart Miller of Bell Laboratories in 1969, with regard to the emerging interest in light wave communications. OEICs has seen their major exploitation in the field of telecommunications due to their pertinent advantages such as low power requirements, low transmission loss, higher bandwidth and immunity to electromagnetic interference. In the 1970s and early 1980s, most work were focused on demonstrating devices that were compatible with the technologies of integrated optics. The distributed feedback (DFB) laser demonstrated in 1972 represents one milestone in this path. After that, a rich variety of passive/active components such as Y-branches, waveguide crossings, grating devices, acousto-optical filters, magneto-optical isolators, electro-optical switches, pulse generators and modulators were demonstrated and developed on different materials systems, utilizing many different operating mechanisms. These rapid developments of optoelectronic components are crucial, predominantly for the next generation of high speed optical communication network.

In view of the swift deployment of wavelength division multiplexing (WDM) network, this has required that OEICs follow high bit rate, high capacity and high bandwidth system requirements. Particularly, this will require signal routing and coupling devices to have large optical bandwidth and to be polarization insensitive as well as small in dimensions and improved fabrication tolerance in order to reduce process costs and contribute to large scale of OEICs production (Soldano and Pennings, 1995). This has consequently resulted in the development of complex OEICs with the accent of improving the existing and developing novel devices. With the advent of multimode interference (MMI) effects on optical devices more than a decade ago, all of the above requirements can be tranquilly fulfilled due to their excellent properties and ease of fabrication. As a result, these have led to their widespread and rapid incorporation in OEICs applications.

Most type of OEICs use optical waveguides as interconnections, as well as being integral parts of both passive and active devices, such as splitters and switches, respectively. In parallel with the development of devices with complicated functionality, various designs of optical waveguide structures have been investigated and utilized. In order to achieve the superb performance of OEICs, these optical waveguides structures are desired to have essential qualities such as high transparency, low cost and high physical, chemical, mechanical, electrical and thermal stability (Tomme *et al.*, 1991). Because of this, it is worth to state that the major performance of OEICs relies on its waveguiding components. Knowing the importance of optical waveguides in OEICs realization, the key factor that needs to be considered is the material systems.

Material research for optoelectronic application has been started extensively few decades back since there is great demand for components that meet performance criteria as well as economic requirements. Few materials with different advantages have been explored and used for the fabrication of optical waveguides, as well as the integrated components. These materials include III-V compound semiconductors, silica, $LiNbO_3$, sol-gel based materials and polymers. These materials have their own advantages and disadvantages as compared to their counterpart. For example, the III-V semiconductors are unique in monolithic integration among waveguides, light sources and detectors. However, the complexity of fabrication, high cost of III-V growth technology, high fiber to chip coupling and waveguide loss present challenges for its practical applications in OEICs. On the other hand, polymers which are considered as one of the recent material for optical waveguides, has received great attention due to its pertinent advantages. Such advantages are low loss, smaller birefringence, exhibiting electro-optic and thermo-optic effects, environmentally stable, high yields and low cost (Eldada, 2002). Many types of fabrication techniques are proposed and currently being employed to fabricate these waveguides. These include classes of deposition techniques, ion-exchange, thermal diffusion, ion implantation, epitaxial growth, lithographic patterning, dry etching and wet etching. However, the selections of these techniques are highly motivated by two reasons: suitability of material systems and cost limitation.

As such, cost limitation and optical devices performances are two main factors that motivated the area of interest in this research. These factors can be solved ideally by two features: one is by employing polymer based material system which is naturally cost-effective and viable in its implementation; the other is by employing MMI effect due to its advantages in realizing optical devices with large fabrication tolerances and optical bandwidth (Besse *et al.*, 1994), compactness (Nagai *et al.*, 2002), polarization insensitive (Soldano and Pennings, 1995) and suitability for device integration (Jenkins *et al.*, 1994) which are the subjects of interest in high capacity WDM network.

## 1.2 A Review on Polymer Based Optical Waveguides and Multimode Interference (MMI) Based Interconnection Devices

Polymer based optical waveguides and devices have attracted a lot of attention with regard to applications in the all-optical network, basically, because they have the potential of added optical functionality and because they may be producible at low cost. This has resulted in rapid research of optical polymers, particularly by the research institutes and chemical companies in order to come out with polymer solution that offers desired optical performance in terms of low-loss, smaller birefringence, high tunability of electro-optic and thermo-optic effects, environmentally stable, high yields and low cost. The classes of optical polymers that were engineered and commercially available for use in OEICs applications include acrylates (Booth, 1989), polyimides (Kobayashi *et al.*, 1998), polycarbonates (Booth, 1989) and olefins (Kane and Krchnavek, 1995). Depending on the addition of the photo crosslink agent (Strandjord *et al.*, 1997), these polymers can be further divided into photosensitive and non-photosensitive type. Much effort has been endeavoured in researching for the waveguides fabrication techniques that suit the nature of the engineered polymers. The most common is the photolithography and etching technique, whereby the desired structures are patterned on the polymer before etching is done. Two types of etching techniques are available: wet etching and dry etching techniques which are significantly applied to the photosensitive and non-photosensitive type of polymers, respectively. Apart from that, other available non-etching fabrication techniques are diffusion and poling (Booth, 1989). According to Booth (1989), diffusion process is related to the movement of external dopants or internal monomers, while poling is based on the monomers reaction as a result of applied electric field. The selection of possible fabrication technique for any optical polymer is highly depending on the prime issues of polymer suitability and cost limitation. In terms of fabrication cost, photosensitive polymers are preferred due to significant advantageous such as low cost materials and low cost processing equipments (Eldada, 2002). Many efforts have been established by the research groups worldwide in the development of polymer based optical waveguides. As a matter of extensive comparisons, few established researches have been dictated to represent the numerous available work from the literatures. The survey on type of developed polymers and its specifications are summarized in Table 1.1. From the table, it shows that the optical polymers with propagation loss as small as 0.07 dB/cm up to 5.4 dB/cm have been employed in optical waveguides and devices applications. Evidently, this propagation loss range can be accepted as the practical benchmarking for any employed optical polymer in optoelectronic applications.

**Table 1.1: Summary of developed polymer based optical waveguides and its specifications**

| Polymer | Type | Fabrication Technique | Wavelength (nm) | Propagation Loss (dB/cm) |
|---|---|---|---|---|
| Acrylate (Booth, 1989) | Photosensitive | Internal polymerization based diffusion | 1550 | 1.2 |
| Polyimides (Sullivan *et al.*, 1992) | Non-photosenstive | Photolithography + Reactive Ion etching | 830 | 0.3 |
| Fluorinated polyimides (Matsuura *et al.*, 1993) | Non-photosenstive | Photolithography + Reactive Ion etching | 1310 | 0.3 |
| Benzocyclobutene (Kane and Krchnavek, 1995) | Photosensitive | Photolithography + Wet etching | 1310 | 0.81 |
| Polymethyl methacrylate (Keil *et al.*, 1996) | Non-photosenstive | Photolithography + Reactive Ion etching | 1550 | 0.9 |
| Fluorinated polyimides (Robitaille *et al.*, 1996) | Photosensitive | Photolithography + Wet etching | 830 | 0.6-1.1 |
| Deuterated polysiloxane (Usui *et al.*, 1996) | Non-photosenstive | Photolithography + Reactive Ion etching | 1550 | 0.4 |

| | | | | |
|---|---|---|---|---|
| Deuterated polyfluoro-methacrylate (Yoshimura *et al.*, 1998) | Non-photosenstive | Photolithography + Reactive Ion etching | 1310 | 0.1 |
| Fluoracrylate (Keil *et al.*, 2000) | Non-photosenstive | Photolithography + Reactive Ion etching | 1550 | 0.8 |
| UV-curable resin (Musa *et al.*, 2000) | Non-photosenstive | Photolithography + Reactive Ion etching | 633 | 1.9 |
| Sol-gel based siloxane (Utaka *et al.*, 2002) | Photosensitive | Photolithography + Wet etching | 1550 | 0.6 |
| G-line photoresist (Hsu *et al.*, 2002) | Photosensitive | Photolithography + Wet etching | 633 | 1.8 |
| Polyimide (Mune *et al.*, 2003) | Photosensitive | Photolithography + Wet etching | 1550 | 0.4 |
| Perfluoro polymer (Yeniay *et al.*, 2004) | Non-photosenstive | Photolithography + Reactive Ion etching | 1550 | 0.07 |
| Epoxy based polynorbornene (Mule' *et al.*, 2004) | Photosensitive | Photolithography + Wet etching | 1550 | 0.5-5.4 |
| Polymethyl methacrylate (Rabus *et al.*, 2005) | Non-photosensitive | Deep Ultra Violet-Induced Modification | 1550 | 1.0 |

Optical polymers have been widely being used in the development of both active and passive optical devices. In active devices, the guided waves that are confined in waveguides can be controlled using external input signals to achieve functional waveguide devices. Physical phenomena used to control guided waves are electro-optic (EO), acousto-optic (AO), magneto-optic (MO), thermo-optic (TO) and nonlinear-optic (NO) effects (Nishihara *et al.*, 1989). The basic building block of these active devices are passive interconnection devices which provide the basic optical guiding and routing application. Passive interconnection optical devices can be of many forms which include Y-branch, directional coupler and Multimode Interference (MMI) based devices.

Since its brief introduction by Soldano et. al. (1992), MMI effect has gained widespread usage in optical interconnect applications such as power coupling, splitting, switching and wavelength multiplexing, particularly due to its broad advantages such as compactness, polarization insensitivity and large fabrication tolerances. In addition, the advent of high speed and high capacity WDM network has further requires the optical interconnection devices to have large optical bandwidth and compact in size for possible integration which has relatively speed up its application.

However, most of these MMI based interconnection devices have so far been fabricated in high index contrast materials such as optical switch in InGaAsP/InP (Nagai *et al.*, 2002), Mach-Zehnder Interferometer (MZI) in InGaAsP/InP (Soldano *et al.*, 1994), splitters in GaAs/AlGaAs (Heaton *et al.*, 1992), optical switch in GaAs/AlGaAs (Jenkins *et al.*, 1994), splitters in $SiO_2$/SiON (Lagali *et al.*, 1998), wavelength demultiplexer in $SiO_2$/SiON (Paiam *et al.*, 1995), splitters made by ion-exchange in glass (Blahut *et al.*, 2004) and couplers in silicon-on-insulator (Jin Song *et al.*, 2004). This is due to conventional thoughts that waveguides exhibiting weak guiding as a result of low index contrast materials cannot produce efficient MMI devices such as quoted by West and Honkanen (2004). Yet, it has been proved by Fardad and Fallahi (1999) that the low index contrast materials system can be efficiently applied in the development of MMI based devices. They have successfully demonstrated 1×32 MMI power splitters with excellent properties through the use of sol gel material on silica. Following this, a work on polymer based MMI interconnection devices have been increasingly demonstrated such as work on splitters by Hsu *et al.*, (2002); Mule' *et al.*, (2004); Rabus *et al.*, (2005) and optical switch by Fan Wang *et al.*, (2006). In addition, numbers of design efforts on polymer based MMI optical devices have been worked out by few groups such as MMI-MZI thermo-optic switch (Chong and Shaari, 2004) and MMI-MZI electro-optic switch (Shi *et al.*, 2002).

Undoubtedly, the observed scenario deeply requires more research contributions in the development aspect of polymer based MMI interconnection devices. Appreciably, in research for cost effective optical interconnections with desired optical performance for current and future high speed and high capacity network, a cost-effective photosensitive based polymer and MMI effect on devices are the potential candidates.

## 1.3 Problem Formulation

For the past few years until now, there are extensive needs to research for good and tolerable performances of optical devices, especially the basic optical interconnection devices (routing, coupling, splitting and wavelength multiplexing) which are cost effective in nature. These devices are primarily important for the successful application of OEICs in high speed and high capacity network such as WDM. Characteristics such as low loss, polarization insensitive, low crosstalk, compactness, device integration feasibility, fabrication tolerances and large optical bandwidth are crucially needed to maintain the intended optical network performances. Motivated from the cost-effective nature of photosensitive based polymer, a BenzoCyclobutene (BCB 4024-40) polymer from Dow™ Chemical Co. is chosen as the material of interest in this research. Primarily, this polymer is ingeniously employed in the development of single mode optical waveguides which are the basic structure of any optical devices and further applied in the development of optical interconnecting devices based on MMI effect which is testified to own broad advantages. The implementation of MMI effect in photosensitive BCB 4024-40 polymer, in researching for the cost effective and good optical performances of optical interconnection devices is formulated to be the principal problems that paving the track of this thesis work.

Based on previous literature surveys, it was found out that the proposed MMI devices based on the photosensitive BCB 4024-40 polymer can be considered as the first ever development work. As such, it is significant to mention the novelty of this research which can contribute to the enhancement of knowledge, predominantly in the field of polymer based photonic devices.

## 1.4 Objective of Research

From the formulated problem which is addressed in the past section, the objective of this research work can be stated as follows:

To embark on the development of optical waveguides and Multimode Interference (MMI) optical interconnection devices particularly the splitters, cross couplers, splitter-combiner, wavelength multiplexer-demultiplexer and thermo-optic switch based on photosensitive BenzoCyclobutene (BCB 4024-40) polymer at the third optical window of 1550 nm central wavelength, as to come out with the device designs and prototypes that are naturally cost effective and posse good and tolerable optical performances.

## 1.5 Scope of Research

In order to achieve the objective of this research, the following scope of work have been identified which comprises of:

1. Characterization of the photosensitive BenzoCyclobutene (BCB 4024-40) polymer in terms of its refractive index, material loss and film thickness with regard to the fabrication parameters.
2. Evaluation of the waveguide fabrication recipes provided by the BCB 4024-40 polymer manufacturer, Dow™ Chemical Co. Further modification on the recipes are to be done in accordance to the available fabrication facilities and desired waveguides and devices specifications
3. Modelling and simulation of single mode optical waveguides at 1550 nm wavelength.

4. Mask design for waveguide patterning and fabrication.
5. Fabrication of the single mode optical waveguides structure.
6. Characterization of the fabricated single mode optical waveguides in terms of its propagation loss, light confinement and physical structure.
7. Modelling and simulation of MMI based interconnecting devices, which include the splitters, cross couplers, splitter-combiner, coarse wavelength multi-demultiplexer and thermo-optic switch at 1550 nm wavelength.
8. Mask design for MMI devices patterning and fabrication.
9. Fabrication of the above mentioned MMI based devices. However, no fabrication work will be imposed on thermo-optic switch development, which is totally a modelling effort.
10. Characterization of the fabricated MMI interconnecting devices in terms of its physical structure, insertion loss, crosstalk and light confinement.

Note that the development processes of single mode optical waveguides are considered as a basic framework for the development of MMI devices. This is due to the fundamental concept of single mode optical waveguides which provides beneficial development outline for more complicated optical devices in terms of device modelling, fabrication and characterization.

## 1.6 Overview of Thesis

As described previously, this thesis is significantly dedicated towards the development of optical waveguides and MMI interconnecting devices based on photosensitive BCB 4024-40 polymer. In order to briefly describe these development stages, the following overview may assist the reader at glance.

Chapter 2 presents the main principles of optical waveguide theory that are used in this thesis. Starting from the Maxwell's equations, the general wave equation which describes the propagation of light in the optical waveguide is derived. Following this, the eigenvalue equation for slab waveguide has been obtained using the ray-optics approach and wave-optics approach. The eigenvalue equation can be used to further obtain the cut-off condition for slab structure. The modelling techniques of channel waveguides have been proposed and discussed in detail, which include, the Effective Index Method, Finite Difference Method and Two-Dimensional Beam Propagation Method. In order to cater for waveguide having non-rectangular sidewall structure, its modelling based on Two-Dimensional Beam Propagation Method has been proposed.

Chapter 3 provides an overview on the fundamentals of Multimode Interference (MMI) effect, applied in this work. The basic self imaging principle that leads to the formation of output images through modes interference is discussed in detail. Two types of interference mechanism have been elaborated, namely, General Interference and Restricted Interference. The Restricted Interference can be further divided into Paired Interference and Symmetric Interference. The mathematical formulations that differentiate the properties of these interference mechanisms are briefly described.

Chapter 4 emphasizes on the BCB 4024-40 polymer characterization and single mode optical waveguide design, fabrication and characterization. Along the way, various issues have been resolved and explained in detail that include the material characterization techniques, waveguide design methodologies, fabrication recipes, waveguide grinding and polishing steps and waveguide characterization techniques.

Based on the waveguides development process in Chapter 4, Chapter 5 covers the development of MMI devices, starting from the design and simulation aspects of BCB 4024-40 polymer MMI devices, followed by fabrication and characterization steps. Four MMI based interconnecting devices have been designed, fabricated and characterized namely; splitters, splitter-combiner, cross couplers and coarse wavelength multiplexer-demultiplexer. Brief comparisons with other similar devices, obtained by other researchers have been included in order to distinguish the significant contributions obtained from this work. For future embarkation on active devices, an optical switch structure based on thermo-optic effect on MMI structure has been proposed. This structure is simulated to function well where the switching characteristics analysis are based on the application of a new thermal analysis method.

Finally, Chapter 6 remarks the overall conclusions and research contributions of this thesis and discusses possibilities for further development of this work.

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